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BEAM-PLASMA HEATING MODEL CODE AND COMMENTARY.(U)

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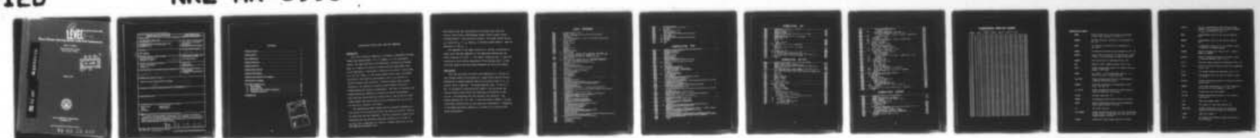

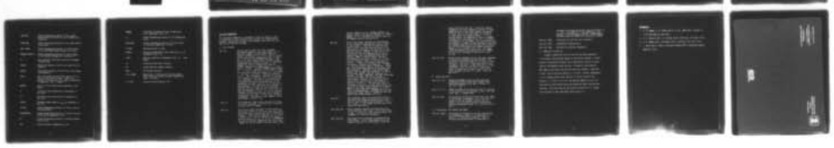

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NRL Memorandum Report 3995

# Beam–Plasma Heating Model Code and Commentary

KENT A. GERBER

*Experimental Plasma Physics*
*Plasma Physics Division*



May 8, 1979



NAVAL RESEARCH LABORATORY
Washington, D.C.

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A computer code listing, definition of terms, and CSN step commentary are presented as a supplement to the paper "Beam-Plasma Heating Model", by D. A. Hammer, A. W. Ali and myself. Together, these papers should allow application of our heating code to a wide and varied range of beam and plasma parameters and resistivity models.

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CONTENTS

## BEAM-PLASMA HEATING MODEL CODE AND COMMENTARY

### INTRODUCTION

This code listing and commentary is intended to supplement the paper, "Beam-Plasma Heating Model," by D. A. Hammer, A. W. Ali and myself.[1] Briefly, the paper describes a one-dimensional ionization and heating model as it applies to results of several electron beam-plasma interaction experiments. Beam energy is deposited resistively in the plasma at a rate $\eta j^2$, where j is the return current density and $\eta$ the plasma resistivity, both classical and anomalous, due to ion-acoustic or electron-electron mode turbulence. Principle energy losses include ionization, line radiation, inelastic electron impact excitation, bremmstrahlung and radiative recombination. The level of ionization and plasma heating are computed as a function of neutral gas pressure, beam rise-time, pulse width and current density, and resistivity model. Plasma dynamic and kinetic effects such as expansion and end loss are not explicitly included in the model.

The computational model assumes that the avalanche breakdown process driven by the large electrostatic and inductive electric fields at the beam front has been completed. Previous theoretical studies[2] have determined that the resultant plasma has a density of the order of $10^{14}$ $cm^{-3}$ and a temperature of a few eV. Plasma conductivity is then

Note: Manuscript submitted March 5, 1979.

Sufficiently high that neutralization of the beam front inductive electric field drives a backstreaming plasma "return current" within the beam channel.[3] When the beam is present, the plasma current density $j_p$ is given by $j_p \simeq - j_b$, where $j_b$ is the beam current density. When the beam pulse is over $j_p = 0$.

The remainder of this paper consists of a listing, a definition of terms, and a CSN step commentary of the beam-plasma heating code set forth in Section II of Ref. 1. This report, along with Ref. 1, should be sufficient to allow further application of this heating code to a wide and varied range of beam and plasma parameters and resistivity models.

CODE LISTING

This code calculates the density and temperature in a "return current" heated plasma in the presence of a large initial neutral fraction. Avalanching is assumed completed when the calculation starts (i.e., no electric field is applied). The energy equations (Eqs. (9) and (11), Ref. 1) calculated in subroutine FINI, ENTRY F, include Spitzer and electron neutral resistivities and three-body recombination as heat sources. Loss mechanisms are line radiation and ionization. The density equation (Eq. (10), Ref. 1) also calculated in ENTRY F, includes collisional ionization and two and three-body recombination. Integration of the energy and density equations is carried out by subroutine INT (Boris and Windsor).[4]

# MAIN PROGRAM

```
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION Y(3)
      REAL*8    TIME(100),TEMP(100),DENSE(100),CNEUT(100)
      COMMON/CALLS/NOCALL
      EXTERNAL F
       CALL PDSTOP
      READ (5,13,END=1000) IMAX,JMAX,TE0,Y20,DENMAX,HO,TPULSE,BKG
   13 FORMAT (2I3,6D10.2)
      C1=3.0D+22
      DO 101 J=1,JMAX
      TE=TE0
      Y(1)=1.5*Y20*TE0
      Y(2)=Y20
      Y(3)=Y(1)
      T=0.D+00
      H01=HO
      IH01=H01*1.D+09
      ITIME=0
      ENERGY=0.D0
      READ (5,14) CURDEN
   14 FORMAT (1D10.2)
      WRITE (6,111)
  111 FORMAT (//30X, ' INITIAL VALUES ARE '/5X, 'TIME STEP', 7X,
     1  'I.SNKT',9X, 'DENSITY',6X, 'TEMPERATURE', 5X,'MAX J-BEAM    ',
     2  1X, 'NEUTRAL DENSITY', 5X, 'B(KG)')
      WRITE (6,11) HO,Y(1),Y(2),TE ,CURDEN,DENMAX,BKG
   11 FORMAT(7E15.5/)
      WRITE (6,112)
  112 FORMAT (1X,'T(NS) DENSITY TE    TI  CRDNT RATIO IONIZ RAD',
     1 1X,'LINE RAD CL ION HT  IAC RES  LHHYB RES  CLAS RES',
     2 1X,'SREPS  CUM ENERGY  EE RES')
      CALL FINT (CURDEN,DENMAX,TPULSE,BKG,H01)
      DO 100 I=1,IMAX
      NOCALL=0
      CALL INT(3,T,Y,F,H01)
      IF(T.LE.TPULSE) GO TO 32
      CRDENT=CURDEN*DEXP(-(T-TPULSE)/1.D-08)
      GO TO 9
   32 CRDENT=CURDEN*(1.D0-DEXP(-T/1.D-08))
    9 CONTINUE
      IF (Y(2).GE.DENMAX) Y(2)=DENMAX
      TE=2.*Y(1)/(3.*Y(2))
      DENEUT=DENMAX-Y(2)
      SQTE=DSQRT(TE)
      VE=4.2D7*SQTE
      SONE=DSQRT(Y(2))
      A=13.6D+00/TE
      DENE=Y(2)
      DENI=DENE
      TI=Y(3)/(1.5D0*DENI)
      SQTI=DSQRT(TI)
      COULOG=24.D0 - DLOG(SONE/TE)
      CLASSR=C1*(COULOG/TE + 0.014D0*DENEUT/DENE)/SQTE
      QI=4.53D-09*COULOG*(TE-TI)*DENE**2/(TE*SQTE)
      CS=9.8D+05*(SQTE+SQTI)
      VTHI=9.8D+05*SQTI
       VD=6.D+21*CRDENT/Y(2)
      ANOMLH=(1.3D+37*BKG/DENE ) *(1.D0/(1.D0+(VTHI/VD)**2))
      ANOMLH=0.D0
      VCRIT=9.8D+05*SQTE*(1.D0+36.D0*(SQTE/SQTI)*DEXP(-1.5D0-0.5D0*TE
     1   /TI))
      RATIO=VD/VCRIT
      IF (RATIO.LT.0.3D+00) RATIO=0.3D+00
       ANOMIA=0.
   20  ANOMIA=(3.6D+30/SONE)*DEXP(-1.D+00/(0.7D0*RATIO**3))
      STABLJ=7.6D-23*DENE**1.5*COULOG/TE**1.5
      CUTOFF=CRDENT/STABLJ
      IF(CUTOFF.LE.0.3D0) CUTOFF=0.3D0
      ANOMEE=0.
   21 ANOMEE=1.D+44*CRDENT/(DENE*SONE)
      ANOMEE=ANOMEE*DEXP(-1./CUTOFF**3)
      ANOMWV=4.D+29*TE/SONE*DEXP(-TE/1000.)
      ANOMWV=ANOMWV*DEXP(-1./CUTOFF**3)
      ANOMWV=0.
      S=5.4D-08*SQTE*DEXP(-A)/(4.88D+00+1.D+00/A)
      S=1.85D+00*DEXP(3.4D+00/TE) * S
      S1=1.6D-6*DEXP(-10.2/TE)/SQTE
      S1=S1/(1.D0+4.7D-14*DENEUT)
      RADION=DENEUT*Y(2)*13.6*S
      RADLIN=DENEUT*Y(2)*S1
      BREMS=3.33D-13*SQTE*Y(2)**2
      RESIST=CLASSR+ANOMLH+ANOMIA +ANOMEE +ANOMWV
      ENERGY=ENERGY+H01*RESIST*CRDENT**2
      ITIME=ITIME+IH01
      EDENS=1.D-15*DENE
      WRITE(6,12)ITIME,EDENS,TE,TI,CRDENT,RATIO,RADION,RADLIN,QI,ANOMIA,
     1 ANOMLH,CLASSR,BREMS,ENERGY,ANOMEE
   12 FORMAT(I5,F6.2,F7.1,F5.1,F6.2,F5.1,9D10.2)
      II=I
      IF (I.GT.50) II=I-50
      IF (I.GT.100) II=I-100
      TIME(II)=T
      TEMP(II)=TE
      DENSE(II)=Y(2)
```

```
      DNEUT(I)=DENEUT
      IF (MOD(I,50).EQ.0) GO TO 50
      GO TO 100
   50 CONTINUE
      IF(I.EQ.100) GO TO 99
      H01=10.D+00*H0
      TH01=H01*1.D+09 +1.D0
      CALL FINI (CURDEN,DENMAX,TPULSE,BKG,H01)
      GO TO 100
   99 H01=25.D0*H0
      TH01=H01*1.D+09
      CALL FINI (CURDEN,DENMAX,TPULSE,BKG,H01)
  100 CONTINUE
  101 CONTINUE
      GO TO 1
 1000 STOP
      END
```

# SUBROUTINE FINI

```
      SUBROUTINE FINI (CURDEN, DENMAX,TPULSE,BKG,H01)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/CALLS/NOCALL
      DSQ=DSQRT(13.6D00)
      RETURN
      ENTRY F(T,Y,DY)
      DIMENSION DY(3)
      DIMENSION Y(3)
      NOCALL=NOCALL+1
      IF(T.LE.TPULSE) GO TO 32
      CRDENT=CURDEN*DEXP(-(T-TPULSE)/1.D-08)
      GO TO 9
   32 CRDENT=CURDEN*(1.D0-DEXP(-T/1.D-08))
    9 CONTINUE
      C1=3.0D+22
      DENE=Y(2)
      DENI=DENE
  101  SQNE=DSQRT(DABS(DENE))
      DENEUT=DENMAX-Y(2)
      IF (DENE.GE.DENMAX) DENE=DENMAX
      IF (DENE.GE.DENMAX) DENEUT=0.D0+00
      TE=Y(1)/(1.5*DENE)
       TE=DABS(TE)
      TI=Y(3)/(1.5D0*DENI)
   11  SQTE=DSQRT(DABS(TE))
      SQTI=DSQRT(TI)
      A=13.6D+00/TE
      S=5.4D-08*SQTE*DEXP(-A)/(4.88D+00+1.D+00/A)
      S=1.85D+00*DEXP(3.6D+00/TE) * S
      S1=1.6D-6*DEXP(-10./TE)/SQTE
      S1=S1/(1.D0+4.7D-14*DENEUT)
      TWOBOD=(5.2D-14*DSQ/SQTE)*(0.43+0.5*DLOG(13.6D+00/TE)+0.469D+00*
     1 (1.D+00/A)**(1./3.))
      THREEB=8.75D-27/TE**4.9
      COULOG=24.D0 - DLOG(SQNE/TE)
      CLASSR=C1*(COULOG/TE + 0.014D0*DENEUT/DENE)/SQTE
      CS=9.9D+05*(SQTE+SQTI)
       IF(T.LT.2.D-09) CRDENT=0.005
       VD=6.D+21*CRDENT/Y(2)
      VCRIT=9.8D+05*SQTE*(1.D0+36.D0*(SQTE/SQTI)*DEXP(-1.5D0-0.5D0*TE
     1 /TI))
      RATIO=VD/VCRIT
      IF (RATIO.LT.0.3D+00) RATIO=0.3D+00
      VTHI=9.8D+05*SQTI
      ANOMLH=(1.3D+37*BKG/DENE ) *(1.D0/(1.D0+(VTHI/VD)**2))
      ANOMLH=0.D0
      STABLJ=7.2D-23*DENE**1.5*COULOG/TE**1.5
      CUTOFF=CRDENT/STABLJ
      IF(CUTOFF.LE.0.3D0) CUTOFF=0.3D0
      ANOMEE=0.
   19 ANOMEE=1.D+44*CRDENT/(DENE*SQNE)
      ANOMEE=ANOMEE*DEXP(-1./CUTOFF**3)
      VE=4.2D7*SQTE
       ANOMIA=0.
   20  ANOMIA=(3.6D+30/SQNE)*DEXP(-1.D+00/(0.7D0*RATIO**3))
      ANOMWV=4.D+29*TE/SQNE*DEXP(-TE/1000.)
      ANOMWV=ANOMWV*DEXP(-1./CUTOFF**3)
      ANOMWV=0.
      ANOME=DABS((VD-CS)/VD)*ANOMIA + 0.5D0*ANOMLH  + ANOMEE +ANOMWV
      ANOMI=(CS/VD)*ANOMIA + 0.5D0*ANOMLH
      QI=4.59D-09*COULOG*(TE-TI)*DENE**2/(TE*SQTE)
      BREMS=3.35D-13*SQTE*Y(2)**2
      RESIST=CLASSR+ANOME
      DY(1)=RESIST*CRDENT**2-DENEUT*DENE*(13.6D+00*S+S1)-BREMS -QI
     1  +THREEB*DENE**3*(1.5D+00*TE+3.D+00)-TWOBOD*DENE**2*1.5D+00*TE
      DY(2)=S*DENE*DENEUT-TWOBOD*DENE**2-THREEB  *DENE**3
      DY(3)=QI+ANOMI*CRDENT**2
      RETURN
        END
```

# SUBROUTINE INT

```
      SUBROUTINE INT (NMAX, X, Y, F, H0)
      INTEGER NMAX
      DOUBLE PRECISION X, H0, Y
      DIMENSION Y(NMAX)
      EXTERNAL F, ERROR
      DOUBLE PRECISION EPS, H, TRUNC, X0, X1, S, Y0, DABS
      INTEGER N, NCONV, NMAX1
      REAL*8 EPSV1
      COMMON /ERRCOM/ Y0(  6), S(  6), EPS, NMAX1
      COMMON/CALLS/NOCALL
      EPS=1.E-5
      NMAX1 = NMAX
      X0 = X
      H = H0
      DO 100 N = 1, NMAX
        Y0(N) = Y(N)
        S(N) = -1
100     IF (Y0(N) .NE. 0.) S(N) = DABS(Y0(N))
      EPSV1=EPS
      EPS=.1
      CALL EXTINT (NMAX, X, Y, F, H, 1, ERROR)
      EPS=EPSV1
      X = X0
      X1 = X + H0
      DO 300 N = 1, NMAX
300     Y(N) = Y0(N)
310   IF (DABS((X1-X)/H) .LE. EPS) GO TO 400
      IF ( (X1-X) * (X1-X-1.4*H) .LE. 0. ) H = X1-X
      IF ( (X1-X-1.4*H) * (X1-X-2.0*H) .LT. 0. ) H = (X1-X) / 2.0
      CALL EXTINT (NMAX, X, Y, F, H, 6, ERROR)
      GO TO 310
400   RETURN
      END
```

# SUBROUTINE EXTINT

```
      SUBROUTINE EXTINT (NMAX, X, Y, F, H0, M MAX, ERROR)
      INTEGER N MAX, M MAX
      DOUBLE PRECISION X, H0, Y(NMAX)
      LOGICAL FIRSTL, CONV(  6), PREVIN, FINISH
      INTEGER J, K, L, M, N, L MAX, K ASIDE, PTS, MM, MMAXP, KMIN
      INTEGER MM2, MMIN, IABS
      REAL FLOAT
      DOUBLE PRECISION X0, U, SUP, YM, BETA, H, DEN, SQRT2, YP, PK,
     1        ONE, TWO, FOUR, SIX, DEXP, DSQRT
      DOUBLE PRECISION HM(11), S(11), P(11,11), YBAR(  6, 7),Y0(  6),
     1        Y NEW(  6), Y OLD(  6), DY(  6), DY0(  6), Y HOLD(4, 7,  6)
      ONE = 1.0
      TWO = 2.0
      FOUR = 4.0
      SIX = 6.0
      MMAXP = MMAX + 1
      SQRT2 = DSQRT(TWO)
      FINISH = .FALSE.
      FIRSTL = .TRUE.
      X0 = X
      DO 100 N = 1, NMAX
100     Y0(N) = Y(N)
      LMAX = (MMAX + 1)/2 + 1
      CALL F (X0, Y0, DY0)
200   X = X0 + H0
      HM(1) = H0/TWO
      HM(2) = H0/FOUR
      HM(3) = H0/SIX
      DO 210 N = 1, NMAX
210     CONV(N) = .FALSE.
      DO 600 MM = 1, MMAXP
        M = MM - 1
        KASIDE = 2
        IF (2*(M/2).EQ.M) KASIDE = 3
        L = (M + 1)/2 + 1
        IF (M.GT.2) HM(MM) = HM(MM-2)/TWO
        H = HM(MM)
        IF (FIRSTL .OR. M.EQ.0 .OR. M.GE.MMAX-1) GO TO 420
          DO 410 N=1, NMAX
410         Y BAR(N,MM) = Y HOLD(1,M,N)
          GO TO 500
420       DO 430 N = 1, NMAX
            Y OLD(N) = Y0(N)
430         Y NEW(N) = Y0(N) + H*DY0(N)
          CALL F (X0+H, YNEW, DY)
          PTS = H0/H + 0.1
          DO 460 K = 2, PTS
```

```
              DO 440 N = 1, NMAX
                 U = Y OLD(N) + TWO*H*DY(N)
                 Y OLD(N) = Y NEW (N)
      440        Y NEW (N) = U
              CALL F (X0 + FLOAT(K)*H, Y NEW, DY)
              IF ((K.NE.KASIDE).OR.(L.LT.2)) GO TO 460
                 DO 450 N = 1, NMAX
      450           Y HOLD (L, M, N) = (YNEW(N) + YOLD(N) + H*DY(N))/TWO
                 L = L - 1
                 KASIDE = 2*KASIDE
      460     CONTINUE
              DO 490 N = 1, NMAX
      490        Y BAR(N,MM) = (YNEW(N) + YOLD(N) + H*DY(N))/TWO
      500  IF (M.GT.0) GO TO 520
           DO 510 N = 1, NMAX
      510     Y(N) = YBAR(N,1)
           IF (MMAX.EQ.0) GO TO 700
           KMIN = 1
           IF (.NOT.FIRSTL) GO TO 600
              BETA = 0.25/(HO*HO)
              S(1) = ONE - DEXP(-BETA*H*H)
           GO TO 600
      520  IF ((3*M)/2 .GT. NMAX) KMIN = KMIN + 1
           IF (.NOT.FIRSTL) GO TO 550
              DEN = ONE
              S(MM) = ONE - DEXP(-BETA*H*H)
              DO 540 K = KMIN, M
                 PK = (H/HH(K))**2
                 DO 530 J = KMIN, M
                    IF (J.NE.K) PK    = PK   *(S(J) - S(MM))/(S(J) - S(K))
      530        CONTINUE
                 P(MM,K) = PK
      540        DEN = DEN - PK
              P(MM,MMAXP) = DEN
      550  DO 590 N=1, N MAX
              IF (CONV(N)) GO TO 590
              YP = Y(N)
              YM = Y BAR(N,MM)
              SUM = 0.0
              DEN = P(MM,MMAXP)
              IF (M.LT.2) GO TO 570
              DO 560 J = KMIN, M
      560        SUM = SUM + (YBAR(N,J) - YP)*P(MM,J)
      570     DY(N) = YM - YP
              IF (DEN.NE.0.0) DY(N) = ((YM - YP) - SUM)/DEN
              Y(N) = YP + DY(N)
      590  CONTINUE
      599  CALL ERROR (N, DY, CONV, FINISH)
           IF (FINISH) GO TO 700
      600 CONTINUE
           HO = HO/TWO
           FIRSTL = .FALSE.
           DO 620 N = 1, NMAX
              Y BAR(N,1) = Y HOLD(2,1,N)
              DO 620 L = 1, LMAX
                 MM2 = MMAX - 2
                 MMIN = IABS(2*L-3)
                 IF (MMIN.GT.MM2) GO TO 620
                 DO 610 M = MMIN, MM2
      610           Y HOLD(L, M, N) = Y HOLD (L+1, M+2, N)
      620     CONTINUE
           GO TO 200
      700 HO = HO * SQRT2 ** (FLOAT(MMAX)*TWO/3.0 - FLOAT(M))
           RETURN
           END
```

# SUBROUTINE ERROR

```
           SUBROUTINE ERROR (M, DY, CONV, FINISH)
           INTEGER M
           INTEGER NMAX, NTIMES( 6), NCONV, N
           DOUBLE PRECISION Y, S, EPS, DABS
           COMMON /ERRCOM/ Y( 6), S( 6), EPS, NMAX
           REAL*8 DY(NMAX)
           LOGICAL CONV(NMAX),FINISH
           IF (M.NE.1) GO TO 1
              DO 3 N = 1, NMAX
      3          NTIMES(N) = 0
              NCONV = 0
      1 DO 2 N = 1, NMAX
              IF (.NOT.( DABS(DY(N))/S(N).LT.EPS .OR. CONV(N) )) GO TO 2
              NTIMES(N) = NTIMES(N) + 1
              IF (NTIMES(N).EQ. 1) NCONV = NCONV + 1
              IF (NTIMES(N).EQ. 2) CONV(N) = .TRUE.
              IF (DABS(Y(N)).GT. S(N)) S(N) = DABS(Y(N))
              IF (Y(N).EQ.0.000 .AND. S(N).EQ.0.000) S(N) = -1
      2 CONTINUE
           IF (NCONV.EQ.NMAX) FINISH = .TRUE.
           RETURN
           END
```

# COMPUTATION PRINT OUT SAMPLE

INITIAL VALUES ARE

| TIME STEP | I.SNRT | DENSITY | TEMPERATURE | MAX J-BEAM | NEUTRAL DENSITY | R(CG) |
|---|---|---|---|---|---|---|
| 0.200000-08 | 0.112500 16 | 0.300000 15 | 0.250000 01 | 0.150000 02 | 0.100000 17 | 0.200000 01 |

| T(NS) | DENSITY | TE | TI | CRONE | RATIO | IONIZ RAD | LINE RAD | CL ION HT | IAC RES | LOWER RES | CLAS RES | BREMS | CUM ENERGY | EE RES |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 0.30 | 2.6 | 7.5 | 2.77 | 6.1 | 0.180 23 | 0.100 21 | -0.860 20 | 0.210 24 | 0.960 23 | 0.750 23 | 0.470 17 | 0.540 16 | 0.000 00 |
| 4 | 0.39 | 12.2 | 4.4 | 4.95 | 4.9 | 0.160 25 | 0.170 22 | 0.120 22 | 0.180 24 | 0.440 23 | 0.980 22 | 0.180 18 | 0.180 17 | 0.000 00 |
| 6 | 0.79 | 14.2 | 5.1 | 6.77 | 3.6 | 0.280 25 | 0.312 22 | 0.370 22 | 0.130 24 | 0.370 23 | 0.680 22 | 0.620 18 | 0.340 17 | 0.000 00 |
| 8 | 1.19 | 12.2 | 4.7 | 8.26 | 2.7 | 0.380 25 | 0.510 22 | 0.110 23 | 0.970 23 | 0.220 23 | 0.730 22 | 0.170 19 | 0.510 17 | 0.000 00 |
| 10 | 1.80 | 10.2 | 4.6 | 9.48 | 2.1 | 0.430 25 | 0.720 22 | 0.230 23 | 0.730 23 | 0.140 23 | 0.850 22 | 0.350 19 | 0.690 17 | 0.000 00 |
| 12 | 2.41 | 8.9 | 4.2 | 10.44 | 1.7 | 0.440 25 | 0.907 22 | 0.410 23 | 0.560 23 | 0.117 23 | 0.100 23 | 0.590 19 | 0.850 17 | 0.000 00 |
| 14 | 3.07 | 8.0 | 4.1 | 11.30 | 1.5 | 0.420 25 | 0.110 23 | 0.610 23 | 0.430 23 | 0.960 22 | 0.110 23 | 0.890 19 | 0.100 18 | 0.000 00 |
| 16 | 3.68 | 7.3 | 4.1 | 11.97 | 1.4 | 0.400 25 | 0.122 23 | 0.820 23 | 0.340 23 | 0.700 22 | 0.120 23 | 0.120 20 | 0.120 18 | 0.000 00 |
| 18 | 4.25 | 6.9 | 4.1 | 12.52 | 1.3 | 0.380 25 | 0.133 23 | 0.100 24 | 0.270 23 | 0.607 22 | 0.130 23 | 0.160 20 | 0.130 18 | 0.000 00 |
| 20 | 4.80 | 6.6 | 4.0 | 12.97 | 1.2 | 0.360 25 | 0.140 23 | 0.120 24 | 0.210 23 | 0.530 22 | 0.140 23 | 0.200 20 | 0.140 18 | 0.000 00 |
| 22 | 5.30 | 6.4 | 4.0 | 13.34 | 1.1 | 0.332 25 | 0.153 23 | 0.152 24 | 0.170 23 | 0.487 22 | 0.150 23 | 0.240 20 | 0.149 18 | 0.000 00 |
| 24 | 5.78 | 6.2 | 4.0 | 13.64 | 1.0 | 0.310 25 | 0.167 23 | 0.172 24 | 0.130 23 | 0.440 22 | 0.150 23 | 0.280 20 | 0.170 18 | 0.000 00 |
| 26 | 6.22 | 6.1 | 4.0 | 13.89 | 1.0 | 0.290 25 | 0.170 23 | 0.190 24 | 0.100 23 | 0.410 22 | 0.150 23 | 0.320 20 | 0.180 18 | 0.000 00 |
| 28 | 6.63 | 6.0 | 4.0 | 14.09 | 0.9 | 0.270 25 | 0.173 23 | 0.212 24 | 0.790 22 | 0.390 22 | 0.150 23 | 0.360 20 | 0.190 18 | 0.000 00 |
| 30 | 7.01 | 6.0 | 4.0 | 14.25 | 0.9 | 0.250 25 | 0.180 23 | 0.232 24 | 0.610 22 | 0.360 22 | 0.152 23 | 0.400 20 | 0.200 18 | 0.000 00 |
| 32 | 7.36 | 6.0 | 4.0 | 14.39 | 0.9 | 0.230 25 | 0.190 23 | 0.260 24 | 0.460 22 | 0.340 22 | 0.150 23 | 0.440 20 | 0.210 18 | 0.000 00 |
| 34 | 7.68 | 6.0 | 4.0 | 14.50 | 0.8 | 0.212 25 | 0.202 23 | 0.289 24 | 0.350 22 | 0.330 22 | 0.150 23 | 0.490 20 | 0.220 18 | 0.000 00 |
| 36 | 7.98 | 6.1 | 4.0 | 14.59 | 0.8 | 0.199 25 | 0.212 23 | 0.310 24 | 0.270 22 | 0.320 22 | 0.150 23 | 0.530 20 | 0.230 18 | 0.000 00 |
| 38 | 8.26 | 6.1 | 4.0 | 14.66 | 0.8 | 0.180 25 | 0.220 23 | 0.330 24 | 0.200 22 | 0.300 22 | 0.150 23 | 0.570 20 | 0.240 18 | 0.000 00 |
| 40 | 8.51 | 6.2 | 4.0 | 14.73 | 0.8 | 0.160 25 | 0.233 23 | 0.363 24 | 0.150 22 | 0.300 22 | 0.150 23 | 0.600 20 | 0.250 18 | 0.000 00 |
| 42 | 8.73 | 6.3 | 4.0 | 14.78 | 0.7 | 0.140 25 | 0.240 23 | 0.380 24 | 0.110 22 | 0.290 22 | 0.140 23 | 0.640 20 | 0.250 18 | 0.000 00 |
| 44 | 8.93 | 6.4 | 4.0 | 14.82 | 0.7 | 0.130 25 | 0.250 23 | 0.400 24 | 0.810 21 | 0.280 22 | 0.140 23 | 0.680 20 | 0.260 18 | 0.000 00 |
| 46 | 9.11 | 6.5 | 4.1 | 14.85 | 0.7 | 0.110 25 | 0.263 23 | 0.420 24 | 0.600 21 | 0.270 22 | 0.130 23 | 0.710 20 | 0.270 18 | 0.000 00 |
| 48 | 9.27 | 6.7 | 4.1 | 14.88 | 0.7 | 0.100 25 | 0.270 23 | 0.440 24 | 0.440 21 | 0.270 22 | 0.130 23 | 0.740 20 | 0.280 18 | 0.000 00 |
| 50 | 9.40 | 6.8 | 4.2 | 14.90 | 0.7 | 0.860 24 | 0.270 23 | 0.460 24 | 0.320 21 | 0.260 22 | 0.133 23 | 0.780 20 | 0.290 18 | 0.000 00 |
| 52 | 9.52 | 7.0 | 4.2 | 14.92 | 0.7 | 0.732 24 | 0.282 23 | 0.472 24 | 0.240 21 | 0.260 22 | 0.120 23 | 0.800 20 | 0.290 18 | 0.000 00 |
| 54 | 9.62 | 7.2 | 4.3 | 14.93 | 0.6 | 0.610 24 | 0.290 23 | 0.480 24 | 0.180 21 | 0.260 22 | 0.120 23 | 0.830 20 | 0.300 18 | 0.000 00 |
| 56 | 9.70 | 7.4 | 4.4 | 14.94 | 0.6 | 0.510 24 | 0.290 23 | 0.493 24 | 0.130 21 | 0.260 22 | 0.110 23 | 0.860 20 | 0.300 18 | 0.000 00 |
| 58 | 9.77 | 7.6 | 4.4 | 14.95 | 0.6 | 0.410 24 | 0.303 23 | 0.500 24 | 0.963 20 | 0.250 22 | 0.112 23 | 0.880 20 | 0.310 18 | 0.000 00 |
| 60 | 9.82 | 7.8 | 4.5 | 14.96 | 0.6 | 0.330 24 | 0.300 23 | 0.510 24 | 0.720 20 | 0.250 22 | 0.110 23 | 0.900 20 | 0.310 18 | 0.000 00 |
| 62 | 9.87 | 8.0 | 4.6 | 14.97 | 0.6 | 0.260 24 | 0.290 23 | 0.512 24 | 0.540 20 | 0.250 22 | 0.100 23 | 0.920 20 | 0.320 18 | 0.000 00 |
| 64 | 9.90 | 8.2 | 4.7 | 14.98 | 0.6 | 0.205 24 | 0.290 23 | 0.510 24 | 0.410 20 | 0.250 22 | 0.980 22 | 0.940 20 | 0.330 18 | 0.000 00 |
| 66 | 9.93 | 8.4 | 4.8 | 14.99 | 0.6 | 0.160 24 | 0.270 23 | 0.520 24 | 0.310 20 | 0.250 22 | 0.950 22 | 0.960 20 | 0.330 18 | 0.000 00 |
| 68 | 9.95 | 8.6 | 4.9 | 14.98 | 0.6 | 0.120 24 | 0.260 23 | 0.520 24 | 0.230 20 | 0.252 22 | 0.920 22 | 0.970 20 | 0.340 18 | 0.000 00 |
| 70 | 9.96 | 8.4 | 5.0 | 14.99 | 0.6 | 0.470 23 | 0.230 23 | 0.520 24 | 0.180 20 | 0.252 22 | 0.890 22 | 0.990 20 | 0.340 18 | 0.000 00 |
| 72 | 9.97 | 9.0 | 5.1 | 12.28 | 0.5 | 0.630 23 | 0.210 23 | 0.510 24 | 0.230 17 | 0.240 22 | 0.870 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 74 | 9.99 | 9.1 | 5.2 | 10.05 | 0.4 | 0.450 23 | 0.172 23 | 0.512 24 | 0.100 12 | 0.232 22 | 0.850 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 76 | 9.99 | 9.1 | 5.3 | 8.23 | 0.3 | 0.310 23 | 0.142 23 | 0.507 24 | 0.140 02 | 0.220 22 | 0.850 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 78 | 9.99 | 9.1 | 5.3 | 6.74 | 0.3 | 0.720 23 | 0.110 23 | 0.490 24 | 0.380 00 | 0.200 22 | 0.950 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 80 | 9.99 | 9.1 | 5.4 | 5.52 | 0.3 | 0.150 23 | 0.850 22 | 0.480 24 | 0.380 00 | 0.180 22 | 0.860 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 82 | 10.00 | 9.0 | 5.5 | 4.52 | 0.3 | 0.110 23 | 0.660 22 | 0.470 24 | 0.382 00 | 0.150 22 | 0.860 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 84 | 10.00 | 9.0 | 5.5 | 3.70 | 0.3 | 0.740 22 | 0.472 22 | 0.460 24 | 0.380 00 | 0.130 22 | 0.870 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 86 | 10.00 | 8.9 | 5.6 | 3.03 | 0.3 | 0.520 22 | 0.363 22 | 0.452 24 | 0.380 00 | 0.990 21 | 0.870 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 88 | 10.00 | 8.9 | 5.6 | 2.48 | 0.3 | 0.370 22 | 0.250 22 | 0.440 24 | 0.380 00 | 0.750 21 | 0.880 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 90 | 10.00 | 8.8 | 5.7 | 2.03 | 0.3 | 0.260 22 | 0.180 22 | 0.420 24 | 0.380 00 | 0.550 21 | 0.990 22 | 0.100 21 | 0.350 18 | 0.000 00 |
| 92 | 10.00 | 8.8 | 5.8 | 1.66 | 0.3 | 0.180 22 | 0.132 22 | 0.410 24 | 0.380 00 | 0.400 21 | 0.890 22 | 0.990 20 | 0.350 18 | 0.000 00 |
| 94 | 10.00 | 8.7 | 5.8 | 1.36 | 0.3 | 0.130 22 | 0.960 21 | 0.400 24 | 0.380 00 | 0.280 21 | 0.900 22 | 0.990 20 | 0.350 18 | 0.000 00 |
| 96 | 10.00 | 8.7 | 5.9 | 1.11 | 0.3 | 0.972 21 | 0.710 21 | 0.390 24 | 0.380 00 | 0.190 21 | 0.910 22 | 0.990 20 | 0.350 18 | 0.000 00 |
| 98 | 10.00 | 8.6 | 5.9 | 0.91 | 0.3 | 0.710 21 | 0.532 21 | 0.380 24 | 0.380 00 | 0.130 21 | 0.920 22 | 0.980 20 | 0.350 18 | 0.000 00 |
| 100 | 10.00 | 8.6 | 6.0 | 0.75 | 0.3 | 0.530 21 | 0.400 21 | 0.370 24 | 0.380 00 | 0.880 20 | 0.920 22 | 0.980 20 | 0.350 18 | 0.000 00 |
| 110 | 10.00 | 8.3 | 6.2 | 0.27 | 0.3 | 0.180 21 | 0.140 21 | 0.320 24 | 0.380 00 | 0.120 20 | 0.940 22 | 0.970 20 | 0.350 18 | 0.000 00 |
| 120 | 10.00 | 8.2 | 6.4 | 0.10 | 0.3 | 0.120 21 | 0.920 20 | 0.270 24 | 0.380 00 | 0.160 19 | 0.990 22 | 0.960 20 | 0.350 18 | 0.000 00 |
| 130 | 10.00 | 8.0 | 6.5 | 0.04 | 0.3 | 0.110 21 | 0.850 20 | 0.220 24 | 0.380 00 | 0.210 18 | 0.100 23 | 0.950 20 | 0.350 18 | 0.000 00 |
| 140 | 10.00 | 7.9 | 6.7 | 0.01 | 0.3 | 0.112 21 | 0.862 20 | 0.192 24 | 0.380 00 | 0.270 17 | 0.100 23 | 0.940 20 | 0.350 18 | 0.000 00 |
| 150 | 10.00 | 7.7 | 6.9 | 0.01 | 0.3 | 0.120 21 | 0.880 20 | 0.150 24 | 0.380 00 | 0.367 16 | 0.112 23 | 0.930 20 | 0.350 18 | 0.000 00 |
| 160 | 10.00 | 7.6 | 6.9 | 0.00 | 0.3 | 0.110 21 | 0.910 20 | 0.120 24 | 0.380 00 | 0.480 15 | 0.110 23 | 0.930 20 | 0.350 18 | 0.000 00 |
| 170 | 10.00 | 7.6 | 7.0 | 0.00 | 0.3 | 0.110 21 | 0.932 20 | 0.102 24 | 0.380 00 | 0.650 14 | 0.110 23 | 0.920 20 | 0.350 18 | 0.000 00 |
| 180 | 10.00 | 7.5 | 7.0 | 0.00 | 0.3 | 0.112 21 | 0.950 20 | 0.822 23 | 0.380 00 | 0.872 13 | 0.110 23 | 0.920 20 | 0.350 18 | 0.000 00 |
| 190 | 10.00 | 7.5 | 7.1 | 0.00 | 0.3 | 0.110 21 | 0.960 20 | 0.660 23 | 0.390 00 | 0.120 13 | 0.110 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 200 | 10.00 | 7.4 | 7.1 | 0.00 | 0.3 | 0.110 21 | 0.972 20 | 0.532 23 | 0.380 00 | 0.140 12 | 0.110 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 210 | 10.00 | 7.4 | 7.1 | 0.00 | 0.3 | 0.110 21 | 0.980 20 | 0.420 23 | 0.380 00 | 0.217 11 | 0.110 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 220 | 10.00 | 7.4 | 7.2 | 0.00 | 0.3 | 0.110 21 | 0.990 20 | 0.330 23 | 0.380 00 | 0.290 10 | 0.110 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 230 | 10.00 | 7.3 | 7.2 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | 0.270 23 | 0.380 00 | 0.390 09 | 0.110 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 240 | 10.00 | 7.3 | 7.2 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.212 23 | 0.380 00 | 0.520 08 | 0.110 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 250 | 10.00 | 7.3 | 7.2 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.170 23 | 0.380 00 | 0.700 07 | 0.110 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 260 | 10.00 | 7.3 | 7.2 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | 0.130 23 | 0.380 00 | 0.952 06 | 0.120 23 | 0.910 20 | 0.350 18 | 0.000 00 |
| 270 | 10.00 | 7.3 | 7.2 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.100 23 | 0.380 00 | 0.130 06 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 280 | 10.00 | 7.3 | 7.2 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.820 22 | 0.380 00 | 0.170 05 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 290 | 10.00 | 7.3 | 7.2 | 0.00 | 0.3 | 0.122 21 | 0.102 21 | 0.640 22 | 0.380 00 | 0.242 04 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 300 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.500 22 | 0.380 00 | 0.320 03 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 310 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.392 22 | 0.380 00 | 0.430 02 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 320 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.122 21 | 0.102 21 | 0.312 22 | 0.380 00 | 0.580 01 | 0.122 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 330 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.240 22 | 0.380 00 | 0.790 00 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 340 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | 0.180 22 | 0.380 00 | 0.110 00 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 350 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.122 21 | 0.100 21 | 0.142 22 | 0.380 00 | 0.140-01 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 360 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.110 22 | 0.380 00 | 0.200-02 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 370 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.810 21 | 0.382 00 | 0.262-03 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 380 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.602 21 | 0.380 00 | 0.360-04 | 0.122 23 | 0.902 20 | 0.350 18 | 0.000 00 |
| 390 | 10.00 | 7.3 | [illegible] | 0.00 | 0.3 | 0.120 21 | 0.100 21 | 0.430 21 | 0.380 00 | 0.480-05 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 400 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.122 21 | 0.102 21 | 0.300 21 | 0.380 00 | 0.660-06 | 0.122 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 410 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | 0.200 21 | 0.380 00 | 0.890-07 | 0.122 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 420 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.200 21 | 0.110 21 | 0.380 00 | 0.120-07 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 430 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | 0.490 20 | 0.380 00 | 0.160-08 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 440 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | -0.202 19 | 0.380 00 | 0.222-09 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 450 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.620 20 | 0.380 00 | 0.300-10 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 460 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | -0.740 20 | 0.382 00 | 0.400-11 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 470 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.122 21 | 0.102 21 | -0.102 21 | 0.380 00 | 0.540-12 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 480 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.122 21 | 0.380 00 | 0.740-13 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 490 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.122 21 | 0.102 21 | -0.142 21 | 0.380 00 | 0.100-13 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 500 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.150 21 | 0.380 00 | 0.140-14 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 510 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.162 21 | 0.380 00 | 0.180-15 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 520 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | -0.172 21 | 0.380 00 | 0.252-16 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 530 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.170 21 | 0.380 00 | 0.330-17 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 540 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.180 21 | 0.380 00 | 0.450-18 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 550 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | -0.180 21 | 0.380 00 | 0.612-19 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 560 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.180 21 | 0.380 00 | 0.830-20 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 570 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | -0.190 21 | 0.380 00 | 0.112-20 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 580 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.190 21 | 0.380 00 | 0.152-21 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 590 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.100 21 | -0.190 21 | 0.380 00 | 0.210-22 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |
| 600 | 10.00 | 7.3 | 7.3 | 0.00 | 0.3 | 0.120 21 | 0.102 21 | -0.190 21 | 0.380 00 | 0.280-23 | 0.120 23 | 0.900 20 | 0.350 18 | 0.000 00 |

DEFINITION OF TERMS

| | |
|---|---|
| ANOME | Electron portion of resistivity as expressed in Eq. (12a), Section II, of Ref. 1. |
| ANOMEE | Electron-electron resistivity as expressed in Eq. (4). |
| ANOMI | Ion portion of resistivity as expressed in Eq. (12b). |
| ANOMIA | Ion-acoustic resistivity as expressed in Eq. (3). |
| ANOMLH | Lower hybrid resistivity not specifically given in Ref. 1, but operative in some of the runs. |
| ANOMWV | Wave resistivity as expressed in Eq. (8). |
| BKG | Applied, axial, magnetic guide field in kG. |
| B(KG) | Format designating printout of initial value of magnetic field BKG. |
| BREMS | $P_B$ in Ref. 1, the plasma power density in $eV/cm^3$ sec lost to bremsstrahlung. |
| CLAS RES | Format designating printout of instantaneous classical resistivity value. |
| CLASSR | Classical resistivity, as expressed in Eqs. (1a), (1b) and (2). |
| CL ION HT | Format designating printout of power density used for classical ion heating. |
| COULOG | Coulomb logarithm, $\ln\Lambda$. |
| CRDENT | Instantaneous beam current density in $kA/cm^2$. |
| CRDNT | Format designating printout of instantaneous beam current density in $kA/cm^2$. |
| CS | Ion sound velocity. |
| CUM ENERGY | Format designating printout of total accumulated energy density transferred from the beam to the plasma system, in $eV/cm.^3$ |
| CURDEN | Assymptotic beam current density in $kA/cm^2$. |

| | |
|---|---|
| CUTOFF | Ratio of instantaneous beam current density (CRDENT) and a minimum current density (STABLJ) or $j_{min}$ as expressed in Eq. (6). |
| DENE | Instantaneous value of the electron density $cm^{-3}$. |
| DENEUT | Instantaneous value of the neutral density $cm^{-3}$. |
| DENI | Instantaneous value of the ion density, equal to DENE for a hydrogen plasma. |
| DENMAX | Neutral hydrogen fill density $cm^{-3}$. Equal to DENE plus DENEUT. |
| DENSITY | Format designating printout of initial value of electron density (Y20) in $cm^{-3}$. |
| DY(1) | Electron energy equation as expressed in Eq. (9). |
| DY(2) | Electron (and ion) density equation as expressed in Eq. (10). |
| DY(3) | Ion energy equation as expressed in Eq. (11). |
| EDENS | Instantaneous value of electron density times $1 \times 10^{-15}$. |
| EE RES | Format designating printout of electron-electron resistivity. |
| ENERGY | Total beam energy density in $eV/cm^3$ deposited resistively in the plasma at a rate $\eta j^2$. |
| HO,HO1 | Calculation time step length. |
| IAC RES | Format designating printout of ion acoustic resistivity. |
| IHO1 | Time step length times $1 \times 10^9$. |
| IMAX | The number of time steps printed out. |
| IONIZ RAD | Format designating printout of beam power density in $eV/cm^3$ sec used for ionization. |
| ITIME | Time step length. |
| JMAX | The number of different current densities to be calculated. |

| | |
|---|---|
| LINE RAD | Format designating printout of the plasma power density in $eV/cm^3$ sec lost through line radiation. |
| LWHYB RES | Format designating printout of the lower hybrid resistivity. |
| MAX J-BEAM | Format designating printout of initial value of the peak beam current density in $kA/cm^2$. |
| NEUTRAL DENSITY | Format designating printout of initial value of the neutral hydrogen fill density $cm^{-3}$. |
| QI | The classical collisional electron-ion energy transfer rate. |
| RADION | Beam power density in $eV/cm^3$ sec used for ionization. |
| RADLIN | Plasma power density in $eV/cm^3$ sec lost through line radiation. |
| RATIO | Ratio of plasma electron drift velocity VD to the critical velocity VCRIT. RATIO is a measure of whether the ion acoustic instability is expected. Yes, if RATIO > 1. |
| RESIST | Sum of all the resistivities employed in the model. |
| S | Ionization rate coefficient as expressed in Eq. (13). |
| S1 | Excitation rate coefficient as expressed in Eq. (14). |
| STABLJ | Minimum current density, $j_{min}$ as expressed in Eq. (6). |
| T,T(NS) | Format designating printout of time in nsec of the calculation. |
| TEMPERATURE | Format designating printout of initial value of the electron temperature in eV. |
| TE | Format designating printout of electron temperature in eV. |
| TEO | Initial electron temperature in eV. |

| | |
|---|---|
| THREEB | Three-body recombination rate coefficient, $\alpha_3$ as expressed in Eq. (16). |
| TI | Format designating printout of ion temperature in eV. |
| TIME STEP | Format designating printout of initial value of time step length (HO) in nsec. |
| T PULSE | Beam pulse width in nsec. |
| TWOBOD | Two-body recombination rate coefficient, $\alpha_2$ as expressed in Eq. (15). |
| VCRIT | Critical velocity as expressed in Eq. (5). (See RATIO). |
| VD | Plasma electron drift velocity. |
| VE | Plasma electron thermal velocity. |
| VTHI | Ion thermal velocity. |
| Y(1),3/2NKT | Defined as 3/2 the initial electron density (Y20) times the initial electron temperature (TEO), in $eV/cm^3$. |
| Y 20,Y(2) | Initial electron density, $cm^{-3}$. |

## CSN STEP COMMENTARY

The following commentary is intended to point out specific areas of importance in understanding and utilizing this computational program. References are made to CSN numbers listed down the left hand side of the code listing.

A. Main Program:

CSN 0007 — Initial data is read in at this statement. The present number of time steps (IMAX) is 100. The total number of beam current densities (JMAX) is presently 6, (2,3,4,6,10 and 15 $kA/cm^2$). The initial electron temperature (TEO) is taken as 2.5 eV, and is determined beforehand. The initial electron density (Y20) is also estimated beforehand, and is usually between 0.1 and 5% of DENMAX, the neutral hydrogen fill density. Present values of Y20 range between $3 \times 10^{13} cm^{-3}$ and $3 \times 10^{14} cm^{-3}$. Values of DENMAX range between $6.7 \times 10^{15} cm^{-3}$ (100mT) and $3.3 \times 10^{16} cm^{-3}$ (500mT). The calculation time step length (HO) is presently $2 \times 10^{-9}$ sec. The first 50 steps are taken at 5HO or 10 nsec increments. See CSN 0083 through 0099, especially 0094 and 0098, for setting the time increments. The time of calculation T(NS) is printed out down the left hand side of the computation printout, see CSN 0027 for this format statement. The beam pulse width (TPULSE) is presently set at 70 nsec for our accelerator. The rise and fall times are set in CSN 0032-0036. They are presently 10 nsec. It is also possible to employ a step function beam pulse by specifying just the rise time. In that case, TPULSE is disregarded. The applied, axial, magnetic guide field (BKG) is set at 2 kG.

CSN 0020 — The assymptotic beam current densities are read in at this statement. One data card is required for each value of CURDEN.

CSN 0023 — This is the format statement for the display of the initial values of the run as they are listed across the top of each section of the computation printout. These include TIME STEP, or HO in nsec, 1.5NKT or Y(1) in $eV/cm^3$, DENSITY, the initial electron density Y20 or Y(2) in $cm^{-3}$, TEMPERATURE, the initial electron temperature TEO in eV, MAX J-BEAM, the initial value of the peak beam current

density CURDEN in kA/cm$^2$, NEUTRAL DENSITY, the initial value of the neutral hydrogen fill density DENMAX, in cm$^{-3}$, and B(KG) the initial value of the magnetic guide field BKG in kG.

CSN 0027 — This is the format statement for the headings of the columns of computational results listed in the printout. From left to right we have: T(NS) in nsec, the time from the start of the beam pulse to the time of the calculation, the electron density, DENSITY, in units of $10^{15}$cm$^{-3}$, the electron and ion temperatures, TE and TI, respectively, the instantaneous beam current density, CRDNT, in kA/cm$^2$, RATIO, the ratio of plasma electron drift velocity, VD, to the critical velocity, VCRIT, as defined in Eq. (5) of Ref. 1. RATIO is a measure of whether the ion acoustic instability is expected. If RATIO > 1, the ion acoustic mode is operative. IONIZ RAD is the beam power density in eV/cm$^3$sec used for ionization. LINE RAD is the plasma power density lost through line radiation. CL ION HT is the power density used for classical ion heating. IAC RES, LWHYB RES, CLAS RES, and EE RES in the last column, are the ion acoustic, lower hybrid, classical and electron-electron resistivities respectively as described in Section II of Ref. 1. They have the units of (eV/cm$^3$sec)/(kA/cm$^2$)$^2$, so that power density is in eV/cm$^3$ sec when current density is in kA/cm$^2$. BREMS is the plasma power density, $P_B$ in Ref. 1, lost to bremsstrahlung. CUM ENERGY is the total accumulated energy density transferred from the beam to the plasma system, in eV/cm$^3$.

CSN 0028 — This statement calls for subroutine FINI which calculates the energy equations given in Eqs. (9) and (11) and the density equation given in Eq. (10) in Ref. 1. The common variables are listed within the parenthesis.

CSN 0032-0036 — These statements specify the beam pulse rise (0035) and fall (0033) time, in this case being 10 nsec. To specify a step function pulse, only statement 0035 would be necessary.

CSN 0038-0080 — Here begins the calculation of quantities for the printout. All of these quantities are defined in Section III of this paper. Note the

order of CSN 0054 and 0055. Since the computer "remembers" the last statement it reads, it takes ANOMLH as zero in this case; ANOMIA, statements 0059 and 0060, on the other hand, is operative, at least within the range of RATIO > 1. In a similar manner, the exponential factor in ANOMEE, statement 0066, and given in Eq. (4), is written in statement 0062 as CUTOFF. The electron-electron resistivity is turned off when the beam current density CRDENT drops below the minimum value required for the electron-electron two stream instability, STABLJ or $j_{min}$ as given in Eq. (6). This same cutoff also limits the wave resistivity, ANOMWV, CSN 0067-0069, although in this run it is set at zero.

CSN 0083-0099 — Within these statements are set the time increments for which the computations are performed. The calculation time step length H0, is set at 2 nsec initially. The first 50 time steps have 2 nsec increments, the next 50 steps have 5H0 or 10 nsec increments, (CSN 0090 and 0094). Additional steps, if more than 100 were called for, would have increments of 25H0 or 50 nsec. (CSN 0093 and 0098).

B. Subroutine FINI:

CSN 0032, 0033 — TWOBOD and TRHEEB are the two and three-body recombination rate coefficients respectively. These are expressed as $\alpha_2$ and $\alpha_3$ in Eqs. (15) and (16) in Ref. 1.

CSN 0057, 0058 — ANOME and ANOMI are the electron and ion portions of the resistivity as expressed in Eqs. (12a) and (12b), Ref. 1, respectively.

CSN 0062-0064 — The equations calculated in subroutine FINI, ENTRY F, are listed in statements 0062, 0063 and 0064, being the electron energy, electron and ion density, and ion energy equations respectively. These are expressed in Eqs. (9), (10) and (11) in Ref. 1.

C. Subroutines, INT, EXTINT and ERROR:

CSN 0005 (INT) — INT chooses an integration accuracy appropriate to the machine on which it is computing, or 1 part in $10^5$, whichever is greater. Then it involves subroutine EXTINT, as necessary to

integrate the energy and density equations from X to X + HO. A description of the arguments of INT appears at the beginning of EXTINT. COMMON/ERRCOM provides subroutine ERROR with variables it needs.

CSN 0010 (INT) Initialize "S" and the local variables.

CSN 0018 (INT) Determine an appropriate H.

CSN 0022 (INT) Perform the required integration.

D. Computation Print Out:

A sample computation printout section has been reproduced to illustrate the existing format of calculation display. Initial values, as previously defined, are listed across the top of each section, and beneath these are the 15 columns of calculations. The sample calculation has initial values as follows: time step 2 nsec, initial electron density $3 \times 10^{14} cm^{-3}$, initial temperature 2.5 eV, maximum beam current density 15 $kA/cm^2$, neutral fill density $1 \times 10^{16} cm^{-3}$ or 150 mT, and applied magnetic field 2 kG. Note that all the resistivities are operative except the electron-electron. Also note how the ion acoustic resistivity is "turned off" at about 75 nsec when RATIO falls below 0.3.

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